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EVALUATION OF DURABILITY-RELATED FIELD INSPECTION DATA FROM CONCRETE BRIDGES UNDER SERVICE

The level of degradation of reinforced concrete bridges was evaluated based on the in-situ measurements performed on five reinforced concrete bridges under service located in the Czech Republic. The combined effect of carbonation and chlorides with respect to the corrosion of steel reinforcement, namely the pH and the amount of water-soluble chlorides, were evaluated on drilled core samples of concrete. Based on these parameters, the ratio between the concentrations of Cl^- and OH, which indicates the ability of concrete to protect reinforcement, was calculated. All the data were statistically summarized and the relationships among them were provided. The main goal of this study is to evaluate the non-proportional effect of the amount of chlorides per mass of concrete on the risk of corrosion initiation and to localize the "critical" locations in the bridges that are the most affected by the degradation effects.

Keyword: Reinforced concrete bridges; field inspection; carbonation process; chloride ingress; corrosion risk

1. Introduction

Bridges in the Czech Republic, as part of Central Europe, are typically exposed to the combined effect of carbonation, chlorides ingress, and mechanical load. Such structures are prone to corrosion that threatens durability and reduces the service life and bearing capacity.

The current design of typical structural elements with respect to exposure conditions is executed by the deemed-to-satisfy rules prescribed by Eurocode 2 [1] and EN 206 [2]. However, when it comes to estimation of service life, current engineering knowledge is not sufficient to provide the number of years with the expected precision. Moreover, it requires a significant amount of research and effort to more precisely determine the load-carrying capacity assessment. Thus, it is important to learn the lessons from the past, to maintain with a high quality and improve the infrastructures according to the best available knowledge.

Thus, it is necessary to gain knowledge on the possible threats to our infrastructure such as corrosion of reinforced steel in concrete bridges and educate engineers on how to deal with such phenomena related to the environmental, or human activities. It is important to focus on the application of best practices, inspections and maintenance of infrastructure, as well as to foster research in numerical modelling and predictive capabilities as well.

Threat mitigation needs precision in identification and description. Thus, the important question is in what is mainly influencing corrosion in case of reinforcing bridges? It is generally accepted that the durability is influenced by the structural properties, loading, and the environment. The structural properties are related to the type of concrete (e.g. Portland cement based only), binary or ternary mixtures [3-5], type of reinforcement (conventional steel, stainless steel, etc. [6]), protection strategies (epoxy-coated reinforcement [7], water proof membrane).

The loading influences directly the load-carrying capacity and safety of the bridges, however its parameters are better described compared to the environmental effect of marine environment or application of chloride-based de-icing agents. So, focusing on the aggressive environment it deserves more attention for both natural sources like sea water and after World War II also a chloride based winter maintenance.

Chlorides from both possible sources penetrate through the concrete to the level of reinforcing steel and support the conditions for the corrosion initiation and subsequent corrosion. It is well known that besides the chlorides, there is also the carbonation effect due to CO_2. The carbonation process

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changes the alkaline protective environment in the concrete by the reaction between carbon dioxide and free hydroxyl ions, thus reducing the pH.

However, the combined effect of carbonation and chloride ingress induced corrosion is usually omitted. It means that the risk of corrosion induced by the actions of chlorides is higher in carbonated concrete compared to the non-carbonated one with higher pH [8,9].

It might seem that the models for the assessment of the corrosion of concrete reinforcement are developed for decades and ready to be implemented with good confidence for expected results. However, this is not yet the case [10].

Knowledge about the behaviour of the real structures is also necessary for the numerical modelling which is under rigorous development worldwide, and this development goes hand in hand with the preparation of Performance-Based Design approach (PBD) for the assessment of durability of existing structures under service in order to improve the authenticity of the available numerical tools.

The question arises how academia might help industry to improve the durability of the existing and future structures. Currently, the discussion and benchmarking on durability calculations based on these deemed-to-satisfy rules have been undertaken by the European technical committees and fib Commissions. It is intended to replace them with PBD in future standards [10,21,22].

Going hand in hand with improving the codes, it is also very important to learn from the past and to analyse the available data. There are the inspections on the bridges regularly going on and the data are available. However, the highway agencies or the industry do not have the capacity to process and analyse the data and deduce some new and important connections and conclusions that could help to improve the design of the structures from the point of view of durability. So, this is, besides the contributions to the code development, another possible role of academia to help to process the data, learn new lessons, and present and provide the information to the engineering public.

In this paper, the data from the regular inspections of highway bridges in the Czech Republic are analysed with respect to the corrosion related durability aspects. The subject of inspection and subsequent analysis are 5 highway bridges [23]. Namely, they are bridge no. 54-040 over a stream that was built in 1937 and inspected in 2014, bridge no. 55I-026a over a local way built in 1976 and inspected in 2014, bridge no. 55I-030 over a river built in 1953 and inspected in 2015, bridge no. 55-033 over a river built in 1963 and inspected in 2016, and bridge no. 57-039 over a river built in 1985 and inspected in 2013.

The field data results are based on the regular inspection with properly selected locations for coring. It is worth mentioning that the selection of the locations and amount of cores to be taken might vary for the individual bridges. One can imagine that if only one location for sampling is selected then the quality of the information from the laboratory analysis is quite low. Thus, this study also explores the effect of the chosen location on the quality and significance of the results and the "critical" locations in the examined bridges are localized. It should be mentioned that some preliminary conclusions from the field measurements of two bridges were already published by the authors of this paper, however, the effect of the core samples locations was not considered there [9].

When assessing the risk of corrosion on the cored samples the threshold value related for the possible corrosion initiation shall be defined based on the aggressive agent. Neville [26] reported that conventional steel reinforcement in concrete is considered to be depassivated if pH drops below 11.8, and usually the reduction of pH is related to the carbonation effect. The other source of aggressive environment for the reinforcement has been also studied worldwide. However, the threshold values reported by research vary significantly [27]. Typically, the chloride ion concentration expressed as percentage per mass of cement is reported, so conversion to the percentage of mass of concrete may be helpful. For instance, authors in [28] reported the chloride threshold to initiate corrosion as 0.4-0.8 [wt.-%/cement] while ACI 201.2R-01 [29] reports 0.1-0.2 [wt.-%/cement]. Another document EN 206 [2] recommends the threshold values of 0.2 or 0.4 [wt.-%/cement] for reinforced concrete and 0.1 or 0.2 [wt.-%/cement] for prestressed concrete. That might be also given as concentration per mass of concrete. The approximate ratio 5.5 for the recalculation from [wt.-%/cement] to [wt.-%/concrete] might be derived when considering for simplicity the weight of cement 400 kg and the weight of concrete without steel 2200 kg, which would be around 0.078-0.145 [wt.-%/concrete] according to [28] and 0.018-0.036 [wt.-%/concrete] according to [29]. The value of 0.1 [wt.-%/concrete] within the range of [30] is considered as a chloride threshold herein.

The high scatter of the chloride threshold values may be related to the strong correlation with the pH of the concrete [8,9,17,30]. As was already mentioned above, the value of the pH related to carbonation of concrete is widely missing [14,16,31,32], thus the comparison of chloride concentration and corrosion risk considering also carbonation effect is of particular interest in this paper. Furthermore, the "critical" locations in the examined bridges that are the most affected by the degradation effects are localized.

2. Methodology

2.1. In-situ inspection

The concrete samples were drilled out of the structures during the regular inspections of the highway bridges under service. The bridges are in the portfolio of Directorate of Highways and Motorways of the Czech Republic. For the individual bridges, the representative locations on girders, abutments, sealing of longitudinal joints between the precast girders, bearing blocks or injection grout in precast girders were selected.

In each location, the three samples were taken from three different depths/layers, 0-10, 10-20 and 20-30 mm from the concrete surface as it is sketched in Fig. 1. Injection grouts were an exception, where only one sample was taken per location.

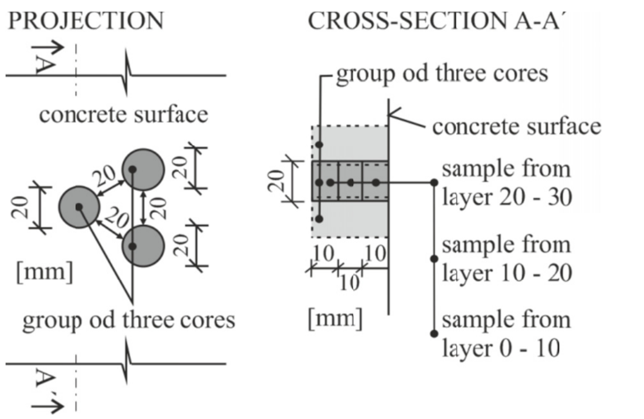

Fig. 1. Illustration of the core samples drilled from one location of the structure

2.2. Laboratory analysis

Drilled concrete samples were analysed for pH and chloride concentration in water leaches in the laboratory [23]. The samples taken from three neighboring locations on the structure (as it is shown in Fig. 1) were homogenized together, separately for each layer, and used for analysis. After homogenization, the amount of 10 g was mixed together with 150 ml of H_2O to obtain a water leach. Subsequently, after filtration, water was added to get a volume of 200 ml. This fusion served for further testing of pH and water-soluble chlorides. For pH measurement the pH-meter with a glass combined electrode was used. Amount of water-soluble chlorides was measured by volumetric analysis/titration of mercuric nitrate solution using diphenyl-carbazone indicator from yellow to violet colour.

Based on the measured parameters, the corrosion risk is expressed as the ratio between the concentrations of Cl^- and OH^- that indicates the ability of concrete to protect reinforcement. In the other words, the higher the ratio, the higher the potential risk of corrosion initiation and propagation. As a critical value $c(Cl^-)/c(OH^-) = 0.6$ is taken into account [8].

2.3. Evaluation of the inspection data

The results were grouped together according to locations on the bridges, taking into account the intensity of the exposure to the aggressive environment. Thus, abutments and bearing blocks are grouped together, girders, cross girders and longitudinal joints are grouped together, and concrete patches and injection grouts are both separated. Attention was focused on three studied parameters: carbonation effect expressed via pH value, chloride concentration given as a percentage by mass of concrete, and the corrosion risk quantified as the ratio of $c(Cl^-)/c(OH^-)$. For all parameters, the statistics of the results were provided by mean values and coefficients of variation.

2.4. Evaluation of the bridge 55I-030

The evaluation of the data proceeded identically for every single bridge. The whole process is shown on bridge 55I-030 in detail. The chosen bridge is a single pole bridge, which bypasses the road I/55I across the Dřevnice river in the center of Otrokovice. The bridge was built in 1953, and diagnostic drilling was carried out in 2015. Thus, the service life in the time of the diagnostic was 62 years.

The Fig. 2 shows the longitudinal and cross sections of the bridge 55I-030. The lower structure consists of two monolithic concrete supports with short parallel wings installed in the upper

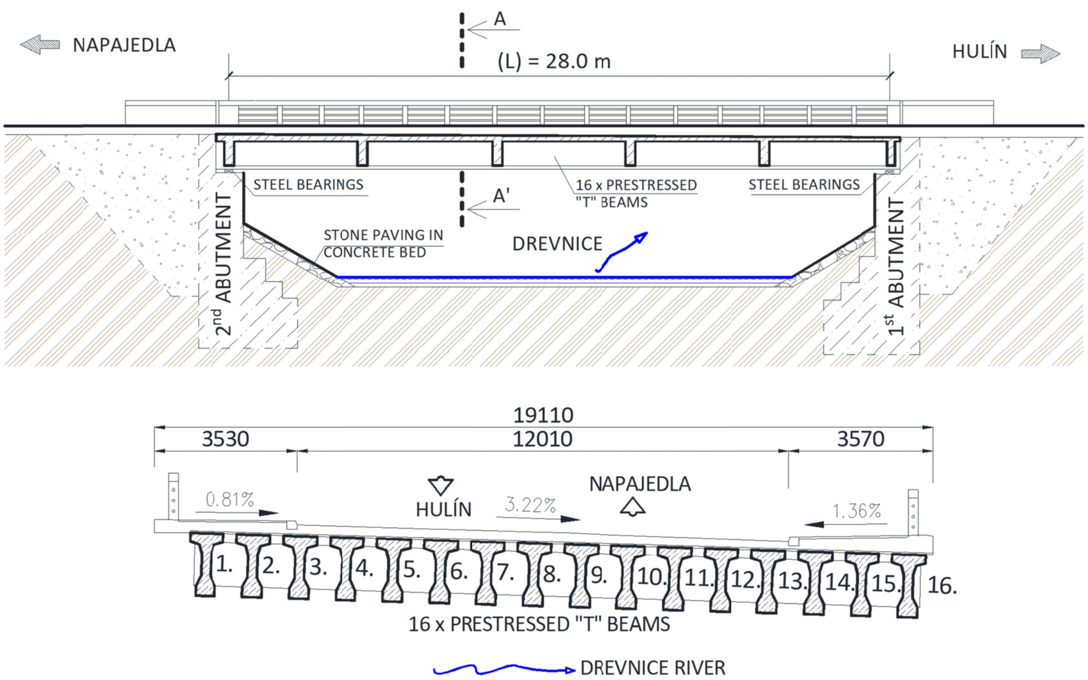

Fig. 2. The longitudinal and cross (A-A’) sections of the bridge 55I-030

part of the abutments. The lower parts of the abutments pass into short retaining walls that are rounded at the beginning and end. The relatively steep slope in front of the abutments is formed by stone paving in a concrete bed running along the entire length of the retaining walls. The girders are supported by steel bearings. The bearings are movable on the first support and fixed on the other one. The horizontal load-bearing structure is a single span, made of 16 prefabricated prestressed "T" beams with the span of 28.0 m over the creek Dřevnice. Thus, the humidity that might foster corrosion and carbonation is provided. So, there is the only source of de-icing chlorides on top of the bridge that is protected by waterproof membrane and asphalt overlay.

The Fig. 3 shows the selected locations of diagnostic drilled holes for the concrete chemical analysis, which is described above. In the case of bridge no. 55I-030 there are 11 sample cores (points from 1 to 11) and 4 sites where the repairing concrete patches has been applied (points 12 to 15).

Totally, there were 15 analysed locations marked as cores with three evaluated depths in points 1-11, and one representative sample in points 12-15. An exception is the investigation of injection grout where only one value represents the core. The mean values and coefficients of variations of studied parameters grouped according to the typical exposition environments are given in Table 1.

It can be seen from the Table 1 that the pH is reasonably high, above 11.63, and the highest value of chloride concentration is 0.23, located at abutments and bearing blocks group. The highest risk of corrosion is also at abutments and bearing blocks. It is 0.6, which is considered to be a threshold [8].

3. Results and discussion for all bridges

Following the methodology for the analysis of bridge 55I-030, the evaluation of the other bridges was processed. The exposure period was considered as the difference between the year of inspection and the year of finalizing the structure, even though it may not be proper for the oldest bridge erected in 1937, as the regular de-icing in the Central Europe started after World War II. The summary of the basic information about the bridges is given in the Table 2. Four of the bridges are above the river, creek, or brook, and one is above the road. It means that bridges

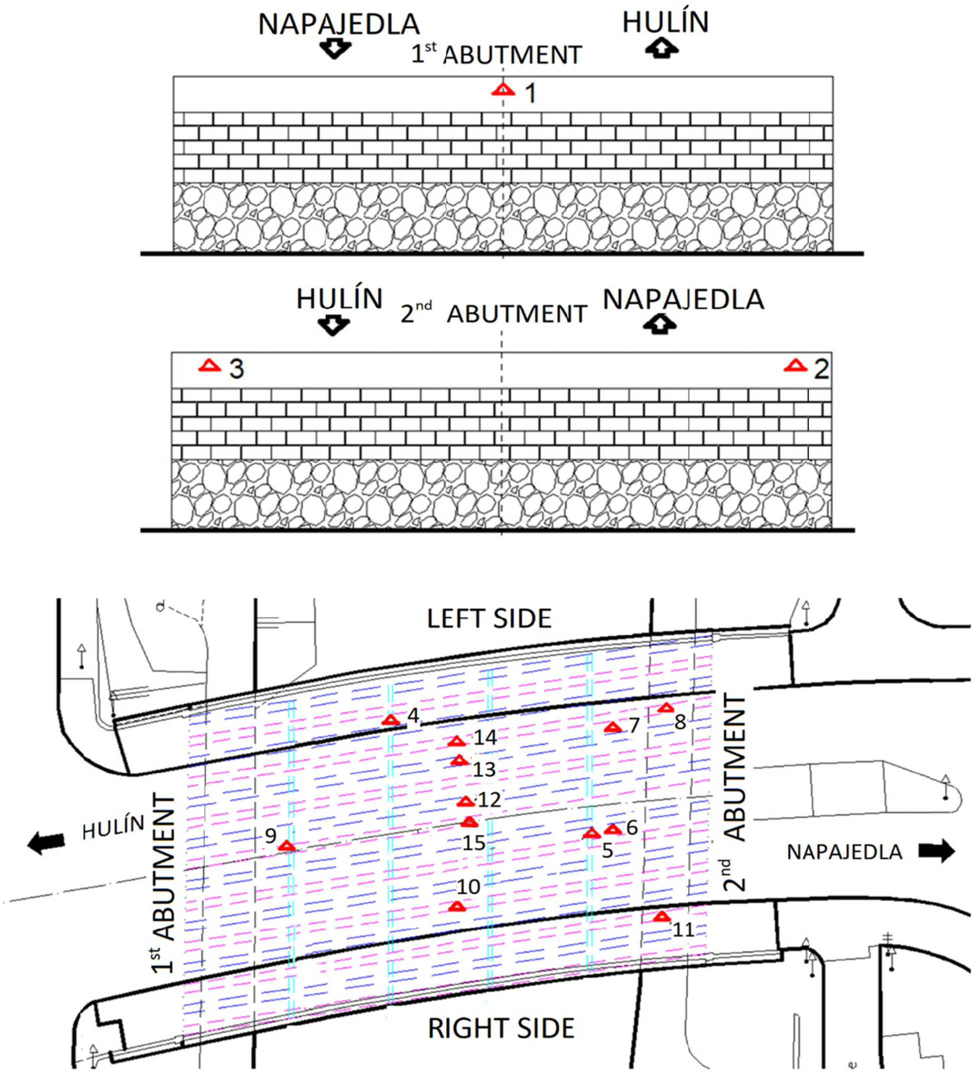

Fig. 3. Front views of the abutments and the scheme of the bridge including sample core spots. Red triangles with represent core positions

TABLE 1

Statistical assessment of the results from field inspection of bridge no. 55I-030: Sample size, carbonation effect (pH), concentration of chlorides (%Cl^-), and corrosion risk described as the ratio $c(Cl^-)/c(OH^-)$ [8] for the complete bridge as well as grouped results per construction component

Bridge: 55I-030		**Amount of samples**		**pH [-]**	**Cl^- [wt.-%/concrete]**	**$c(Cl^-)/c(OH^-)$ [-]**
All samples	Cores	15	Mean	11.53	0.08	0.28
	Layers	37	Co.Var.	0.03	1.69	1.72
Abutments & Bearing Blocks	Cores	3	Mean	11.63	0.23	0.60
	Layers	9	Co.Var.	0.02	0.81	1.02
Girders, Cross Bars & Longitudinal Joints	Cores	8	Mean	11.46	0.03	0.18
	Layers	24	Co.Var.	0.04	16.70	1.19
Concrete Patches	Cores	0	Mean	—	—	—
	Layers	0	Co.Var.	—	—	—
Injecting Grouts	Cores	4	Mean	11.76	0.06	0.13
	Layers	4	Co.Var.	0.01	0.18	0.30
Notes	Bridge overpasses Dřevnice creek in Otrokovice In the column „Amount of samples“ we consider one group of three cores (see Fig. 1) as one sample, because in the laboratory the same layer from all three cores is homogenized together.					

TABLE 2

Summary of the basic information about the bridges

No.	**Bridge**	**Bypasses**	**Built**	**Exposure [years]**	**Sample Size**	
					Cores	**Layers**
1	54-040	Okluky brook behind Slavkov village	1937	77	13	39
2	55I-026a	Minor road in front of Otrokovice	1976	38	13	39
3	55I-030	Dřevnice creek in Otrokovice	1953	62	12	37
4	55-033	Morava river in front of Napajedla	1963	53	20	60
5	57-039	Jičínka creek in Nový Jičín	1985	28	14	43

above water have a source of moisture that increases the rate of carbonation, and the bridge above the road has another source of the chlorides besides the actual de-icing of the bridge itself. The mean values of the studied parameters along with the variation coefficients are given in Table 3.

It can be seen from Table 3 that average values of pH for all the bridges are below the depassivation threshold of 11.8 [26], with the uniform dispersion throughout the sampled cores. The coefficient of variation ranges between 0.03 and 0.11, except for one higher value of 0.16 for bridge 57-039. The Table 3 also reveals that average value of chloride concentration for the oldest bridge is equal to the 0.1 [wt.-%/concrete], which is considered to be the threshold for corrosion initiation within the range given in [28]. The average corrosion risk criterion $c(Cl^-)/c(OH^-)$ gives another perspective. The coefficient of variation (CoVar) in Table 1 indicates a high variability of chloride concentration (0.9 and more with an extreme value of 1.69 for bridge 55I-030). Threshold value of 0.6 is exceeded for three bridges from all those evaluated.

The threshold for the combined effect of chlorides and carbonation is not exceeded for bridges 55I-030 and 55-033. However, the average value does not give information about the problematic components or locations at the bridges. The coefficient of variation for the combined corrosion risk is higher than 1.29 for four bridges. The respective values are up to the highest value of 2.11, which was found on bridge 55I-026a.

3.1. Carbonation effect

Results that are more illustrative are given by splitting the data into the following groups: girder supports such as abutments,

TABLE 3

Summary of the statistics of carbonation effect (pH), chloride concentration (Cl^-) and corrosion risk $c(Cl^-)/c(OH^-)$ for individual bridges

No.	**Bridge**	**pH [-]**		**Cl^- [wt.-%/concrete]**		**$c(Cl^-)/c(OH^-)$ [-]**	
		Mean	**Co.Var.**	**Mean**	**Co.Var.**	**Mean**	**Co.Var.**
1	54-040	9.82	0.10	0.10	0.99	37.61	1.36
2	55I-026a	10.66	0.11	0.07	1.01	22.90	2.11
3	55I-030	11.53	0.03	0.08	1.69	0.28	1.34
4	55-033	11.60	0.04	0.05	1.22	0.23	1.29
5	57-039	9.50	0.16	0.09	0.90	688.79	1.66

bridge deck supporting construction such as girders, concrete patches and injection grouting related to the prestressing tendons (Table 4). One can see that the variation has been generally reduced bellow 0.1. The except is the youngest bridge 57-039, where the value of the variation coefficient dropped from 0.16 to the value 0.11 for abutments and bearing blocks, 0.09 in case of girders and cross bars. The grouping has significant effect to focus on the problematic areas. It allowed to highlight the girders in the case of bridge 54-040, and abutments in the case of bridge 57-039, where the pH is lower to 9 and bridge 55-026a where pH is below 10. The visual representation is shown in Fig. 4.

3.2. Chloride concentration

Looking at the chloride concentration (Table 5), one can see that the variation has generally decreased. The exception to the general trend are bridges 55I-026a and 55-033 in case of the abutments class where the chloride concentration variation has not dropped below the value of 1. Concentration above the considered chloride concentration value of 0.1 [wt.-%/concrete] is evaluated on bridges 54-040, 55I-030 and 57-039. The limit value is also reached on concrete patches of bridge 55I-026a and exceeded in the injection grout of the same bridge. The respective graph is presented on the Fig. 5.

TABLE 4

Carbonation effect described by pH for individual bridges and respective construction components

No.	Bridge	Carbonation effect – pH [-]							
		Abutments & Bearing Blocks		Girders, Cross Bars & Longitudinal Joints		Concrete Patches		Injecting Grouts	
		Mean	Co.Var.	Mean	Co.Var.	Mean	Co.Var.	Mean	Co.Var.
1	54-040	10.48	0.05	8.76	0.02	—	—	—	—
2	55I-026a	9.71	0.08	11.81	0.02	11.70	0.03	11.81	0.01
3	55I-030	11.63	0.02	11.46	0.04	—	—	11.76	0.01
4	55-033	11.79	0.02	11.32	0.05	—	—	—	—
5	57-039	8.55	0.11	10.84	0.09	—	—	11.87	0

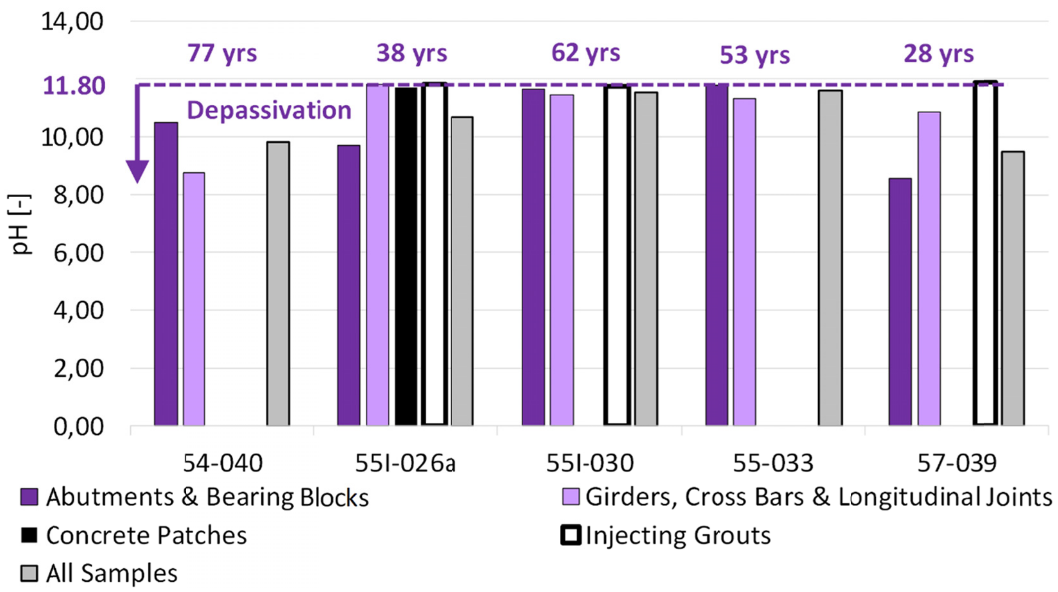

Fig. 4. Carbonation effect described by pH for individual bridges and respective construction members

TABLE 5

Water soluble chloride ion concentration Cl^- [wt.-%/concrete] for selected bridges and respective construction components

No.	Bridge	Chloride Concentration – Cl^- [wt.-%/concrete]							
		Abutments & Bearing Blocks		Girders, Cross Bars & Longitudinal Joints		Concrete Patches		Injecting Grouts	
		Mean	Co.Var.	Mean	Co.Var.	Mean	Co.Var.	Mean	Co.Var.
1	54-040	0.13	0.78	0.04	0.93	—	—	—	—
2	55I-026a	0.07	1.25	0.04	0.52	0.10	0.57	0.11	0.38
3	55I-030	0.23	0.81	0.03	0.69	—	—	0.06	0.18
4	55-033	0.06	1.16	0.04	1.28	—	—	—	—
5	57-039	0.11	0.78	0.03	0.26	—	—	0.08	0.62

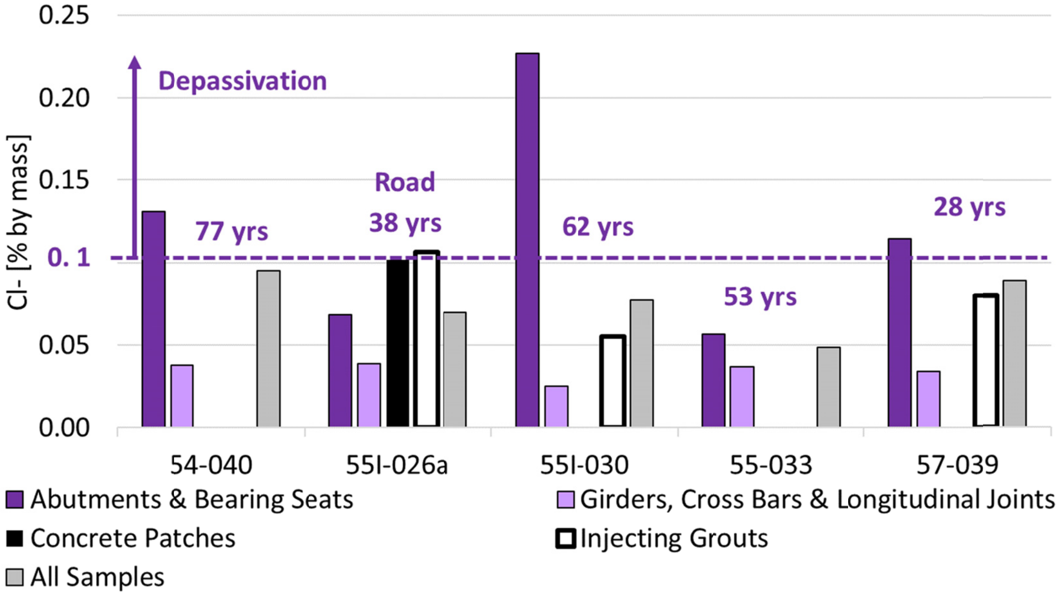

Fig. 5. Water soluble chloride ion concentration Cl^- [wt.-%/cement] [8] for selected bridges and respective construction members

3.3. Corrosion risk via $c(Cl^-)/c(OH^-)$

The $c(Cl^-)/c(OH^-)$ ratio given per groups has shown that the worst situation with respect to corrosion is, in the case of the oldest bridge 54-040 and the youngest bridge 57-039. The $c(Cl^-)/c(OH^-)$ ratios for the two classes (Abutments & Bearing Blocks and Girders, Cross Bars & Longitudinal Joints) are much higher than the critical value of 0.6 (see Table 6). The high corrosion risk is expected in the case of the oldest bridge due to the longest exposure to de-icers. The abutments have $c(Cl^-)/c(OH^-) = 6.29$ and the girder group 87.71, respectively for the bridge No. 54-040. However, that the high risk, in the case of the youngest bridge (No. 57-039), commenced to service in 1985, is surprising. This bridge has problems with the same categories. It has the highest value of $c(Cl^-)/c(OH^-) = 1094.77$ at the abutments and the girder group has the ratio 4.91. It is worth mentioning that also the abutments of the bridge 55I-026a are in severe risk of corrosion. Investigated parameter has the value of 42.35. It is of interest that the injection grouts investigated in three of five bridges have not reached the critical value of 0.6.

Regarding the variation coefficient, the values have dropped, however, five from thirteen CoVar parameters are still above 1.0. So further narrowing would be helpful in case of larger bridge data sets. The highest value is 2.03 in the case of girders of the youngest bridge 57-039 due to the high value of corrosion risk at the longitudinal joint between the precast girders. The girders themselves have the ratio below the critical values, except for surface layer of cores. More specifically, the $c(Cl^-)/c(OH^-)$ ratio was 1.42 and 1.11 in the case of top layer of cores from two girders of the discussed bridge 57-039.

When comparing the corrosion concentration on Fig. 5 with the corrosion risk on Fig. 6, it can be seen that the risk of corrosion follows the pattern of chloride concentration in the case of the oldest and youngest bridge 54-040 and 57-039. This pattern is not the case of the bridge 55I-030, where is the high value of the chloride concentration at the abutments of 0.23 [wt.-%/concrete]. While the corrosion risk is exactly at the threshold 0.6, due to one of the highest values of pH = 11.63. On the other hand, lower pH, meaning more severe reduction of the protective alkalinity of concrete in the case of bridges 54-040 and 57-039, is reflected in the highest values of the corrosion risk ratios. The oldest bridge with the denomination 54-040 has the corrosion risk for the abutments 6.29 and girders 87.71. The youngest bridge 57-039 has the corrosion risk for the abutments 1094.77 and girders 4.91.

The reduction of pH in case of the oldest bridge is attributed to the carbonation. The reason for the lower pH in the case of the

TABLE 6

Corrosion risk described as ratio $c(Cl^-)/c(OH^-)$ [8] for selected bridges and respective construction components

No.	Bridge	Corrosion Risk – $c(Cl^-)/c(OH^-)$ [-]							
		Abutments & Bearing Blocks		Girders, Cross Bars & Longitudinal Joints		Concrete Patches		Injecting Grouts	
		Mean	Co.Var.	Mean	Co.Var.	Mean	Co.Var.	Mean	Co.Var.
1	54-040	6.29	0.79	87.71	0.59	—	—	—	—
2	55I-026a	42.35	1.41	0.10	0.97	0.30	0.71	0.26	0.71
3	55I-030	0.60	1.02	0.18	1.68	—	—	0.13	0.30
4	55-033	0.16	1.25	0.34	1.13	—	—	—	—
5	57-039	1094.77	1.17	4.91	2.03	—	—	0.16	0.76

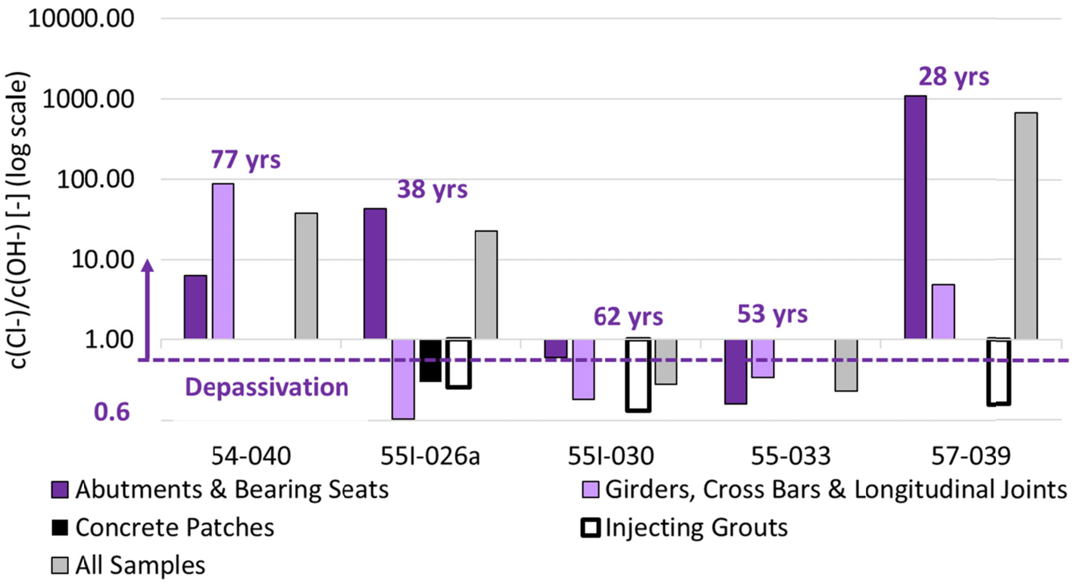

Fig. 6. Corrosion risk described as ratio $c(Cl^-)/c(OH^-)$ [8] for selected bridges and respective construction members

new bridge is unknown. It might be due to the development of higher strength concrete, admixtures, and reduction of Portland cement, which also affects pH of the mixes.

It can be also seen on the example of bridge 55I-026a above the local road that the proper selection of the location for the coring is important. Even though the overall corrosion risk is relatively high, 22.9, all the locations have a ratio below the critical value of 0.6, except the abutments, where the ratio is 42.35. Thus, the idea that the inspection would be satisfactory with several samples only as dictated by the short-term financial feasibility does not seems to be justifiable.

4. Conclusions

1. The analysis of chloride profiles, pH concentration and the $c(Cl^-)/c(OH^-)$ ratio for the chloride induced corrosion risk on the concrete samples is evaluated for 5 selected bridges. The results of 80 cores with 218 samples are analysed.
2. The importance of the larger amount and proper selection of investigated locations is illustrated on the example of the bridge above the road where only abutments have a high risk of corrosion.
3. The variations of resulting concentrations per bridge shows that it is not likely that one sample per bridge would be enough. More samples give a better perspective.
4. A high risk of corrosion in the case of the bridge built in 1985 compared to the older bridges from the sixties, seventies or fifties is surprising and deserves further attention.
5. The further exploration of the available bridge database that contains 15 more bridges is under progress in order to obtain more comprehensive data. Also, further narrowing of the data to abutments, bearing blocks, girders and longitudinal joins between the girders is of future interest.
6. The data sets contain the analysis of the chloride profile at three different depths. Even though the number of data points (investigated layers in cores) will be higher for estimation of the diffusion coefficient, the possibility of deriving it deserves further attention.
7. Chloride profiles and pH values analysed independently have given different answers compared to the $c(Cl^-)/c(OH^-)$ ratio with respect to the risk of corrosion initiation, and thus it is necessary to consider both phenomena simultaneously.

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